Car-to-Car Safety Broadcast with Interference using Raptor Codes

Nor Fadzilah Abdullah*, Angela Doufexi, Robert J. Piechocki
University of Bristol, Centre for Communications Research, BS8 1UB UK.

***Abstract*—Car-to-car safety applications that demand real-time and reliable communications in vehicular ad hoc networks (VANETs) requires a new paradigm of coding techniques. In this paper, we propose a novel coding approach using a systematic Raptor code for car-to-car post-crash warning broadcast applications. A cross-layer simulator model is developed to evaluate the performance of Raptor codes against repetition codes using also multiple antennas spatial diversity techniques. The end-to-end delay and packet delivery ratio are used as performance metrics to demonstrate the latency and reliability problems of repetition codes that are addressed using Raptor codes.**

***Index Terms*—VANETs, WAVE, IEEE 802.11p, Raptor code, Fountain code, MIMO, STBC.**

I. Introduction

With more than 200 million car ownership in the EU, Intelligent transportation systems (ITS) have a direct impact on society. Around 43,000 deaths and more than 1.8 million injuries are reported on the road each year, representing an estimated lost of 160 billion Euros [1]. In turn, the IEEE and ASTM standardization bodies have proposed two standards specifically for vehicular environment, specified in the IEEE 802.11p and Wireless Access for Vehicular Environment (WAVE) standards. The WAVE standard supported two different stacks of Transport and Network layers namely the normal TCP/IP protocol stack and a new proprietary WAVE Short-Message Protocol (WSMP). The WSMP transport is used for high priority, reliable and time-sensitive communications such as car-to-car safety applications. This motivated the design of a new paradigm of coding techniques for car-to-car communications.

Raptor codes [2] originate from the family of fountain codes, also known as rateless codes. These codes are characterized by their flexible coding rate that is adjustable on-the-fly regardless of varying or unknown channel conditions. This is in contrast to conventional codes, where the coding rates are fixed beforehand and prior knowledge of the channel condition is required. Fountain codes for vehicular communications have only recently been studied in [3], [4], [5]. However, these previous works steer towards an infrastructure-dependent communication for value-added service applications. To the best of our knowledge, rateless codes for vehicular ad hoc networks (VANETs) safety applications has not yet been investigated. In this paper, we propose a novel coding approach using a systematic Raptor code for car-to-car post-crash warning broadcast applications.

In our previous work [6], we developed a detailed STBC (space time block code) physical layer simulator that is incorporated into the vehicular ad hoc networks (VANETs) safety application using the proposed parameters in the WAVE standard. It was shown that STBC enhances the delivery range of the emergency safety broadcast. It is well-known that repetition codes come with a number of drawbacks such as high latency and inefficient use of bandwidth that may lead to network congestion. In [7], we enhanced the post-crash warning broadcast by implementing Raptor codes at the application layer, instead of repetition codes proposed in the standard. This analysis was a simple model that did not consider interference from multiple nodes. In this paper, we further enhance the analysis to take into account a scenario with interference from surrounding vehicles. The sources of interference are the periodic vehicle status broadcasts that carry information such as GPS coordinates, speed, and direction.

Our contributions in this paper are twofold. We developed a cross-layer simulator model to evaluate the performance of Raptor codes against repetition codes for both single antenna and the STBC 2x2 and STBC 4x4 multiple antennas spatial diversity schemes. End-to-end delay and packet delivery ratio are used as performance metrics to demonstrate the latency and reliability benefits provided by Raptor codes. In addition, we also propose an analytical model to represent Raptor code performance in this context.

The rest of the paper is organized as follows. Section II gives a brief overview to general and systematic Raptor codes. The safety broadcast system model and MAC modeling is explained in Section III and IV. Numerical analysis are presented in Section V. Finally, Section VI concludes the paper.

II. Brief Overview of Raptor Codes

Raptor codes are a sparse graph code with capacity approaching rates that have been first introduced [2]. A number of standards, namely the 3GPP MBMS (Multimedia Broadcast Multicast Service) [8] and the DVB-Handheld standard for IP Datacasting and commercial IPTV services [9] have formally adopted Raptor codes as the application layer FEC (forward error correction) scheme. In this section, we shall provide a brief overview of a general Raptor code proposed by Shokrollahi and a

*NF Abdullah is also with Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Malaysia.

systematic design of Raptor codes as proposed in the 3GPP standard.

In general, Raptor codes are a concatenated code approach with a high rate precode, typically a Low-Density Parity-Check (LDPC) code as the outer code and a LT (Luby Transform) code as the inner code. A weakened LT code with an average degree of three is used to reduce the computational complexity of the LT code encoding and decoding algorithms from $O(K\,logK)$ to $O(K)$, where K is the source block length or the number of source symbols. However, this will introduce an error floor where the LT decoder normally can only reconstruct a fraction of the entire message block. Therefore, a precode is required to provide extra protection to the source symbols by correcting erasures that are not recovered by the weakened LT code.

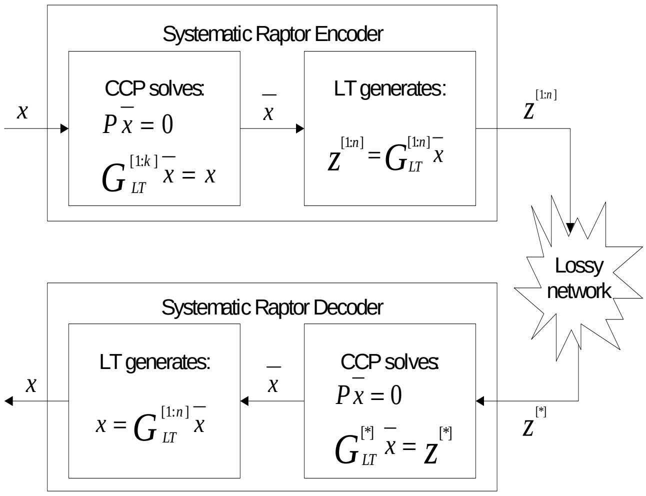

Fig. 1. Systematic Raptor block diagram

Although Raptor codes are non-systematic by construction, direct access to the original data can often be beneficial especially for users with good channel conditions. This property is provided by systematic codes and can be achieved by performing an appropriate linear transformation of the input before the LT encoding step at the transmitter. On the other hand, users which do not observe systematic symbols are still able to reconstruct the set of the intermediate symbols from the rest of Raptor encoded bitstream, and thus indirectly recover the original message by inverting the predescribed linear transformation. The linear transformation of input procedure is as shown in Figure 1 where $x[0], ..., x[K-1]$ are the K source symbols and $\bar{x}[0], ..., \bar{x}[L-1]$ are the L intermediate symbols given that $L = K + S + H$. In the 3GPP systematic Raptor code, P refers to the parity check matrix from the LDPC code, G_{LDPC} (of size $S \times K$) and Half precoding using the properties of Gray sequences, G_{Half} (of size $H \times (S+K)$). For a known K source symbols, the size of the precode can be determined from the relationships in eq. (1)-(3). G_{LDPC}, G_{Half} and G_{LT} need only to be pre-calculated once at the transmitter for a given K source symbols and stored as the precode matrix, A (of size $L \times L$) for future reference.

$$X = min\{x \in \mathbb{N} : x(x-1) > 2K\} \tag{1}$$

$$S = min\{s \in \mathbb{N}, s' : s \geq \lceil \frac{K}{100} \rceil + X\} \tag{2}$$

$$H = min\{h \in \mathbb{N} : \binom{h}{\lceil \frac{h}{2} \rceil} \geq K + S\} \tag{3}$$

A crucial assumption in systematic Raptor design is to ensure that the precode matrix A is invertible i.e. the encoder has full rank L over $GF2$ (Galois Field 2). Additionally, the encoder and the decoder are equipped with a similar pseudorandom number generator. Its output depends on two long pre-calculated arrays $V0$ and $V1$. These arrays serve as a database to form the so called *source triples* that are fed to the pseudorandom number generator. The source triples are read from the arrays according to the current encoded symbols identifier (ESI) that are subsequently numbered according to the position of a processed encoded symbol within the LT encoded stream. The code constraint processor (CCP) is an efficient way to perform the binary inverse matrix operation. Two popular methods to solve this is by using the Gaussian elimination procedure or the iterative belief propagation. The Gaussian elimination method is usually used for smaller block lengths K, while belief propagation method is used for larger K. In the 3GPP MBMS specification, an enhanced Gaussian elimination is proposed. Similarly, in our scenario where a very short K block length of 8 is used, we utilized the Gaussian elimination method.

III. Safety Broadcast System Model

Broadcasting is most suitable for safety message dissemination because it conveys the message to as many as possible vehicles within the vicinity of the sender in the fastest manner. Without routing and forwarding procedures in broadcasting, the safety message can be delivered in a timely manner to these vehicles to warn road users of impending safety hazards and in order for the drivers to make corresponding reactions. WAVE operates at the 5.9 GHz licensed band that is divided into 7 channels. Of these, one is the control channel which is used for high priority safety messages consisting of event-triggered safety broadcast and periodic vehicle status broadcast. We treat the periodic status broadcast as interference and made the assumption that there is no unicast traffic competing for the channel access.

The post-crash warning scenario is illustrated in Figure 2. We name the vehicle transmitting the post-crash warning message as the tagged vehicle. The highway structure is a three lanes bidirectional highway and two different vehicle densities, β. A high traffic density highway, where cars are spaced closer together is represented by a low average speed, v of 50 km/h scenario. In the second scenario of the lower density traffic, we assume a higher average speed of 100 km/h.

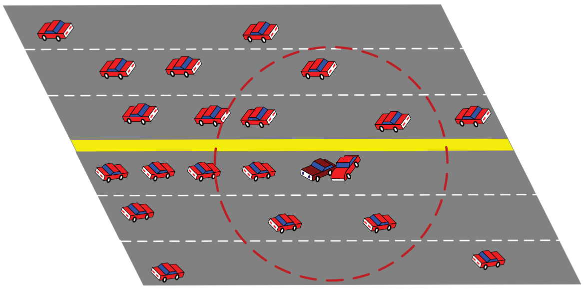

Fig. 2. Post-crash warning on motorways

$$h\left(t\right)=\sum_{n=1}^{L}A_{n}\cdot exp\left(j\left(\phi_{n}-2\pi f_{d}t\cdot cos(\alpha_{n})\right)\right) \tag{4}$$

To represent the time evolution of the $n.i.i.d$ (non-independent identically distributed) multipath Rayleigh channel due to the low transmitter and receiver antenna heights, as well as reflection from moving vehicles and lamp posts, we utilized a time-correlated channel using the Clarke's model in eq. (4). Average speed values, v from different traffic densities are used for the maximum Doppler shift, f_d calculation, where $f_d = \frac{vf}{c}$, v is maximum vehicular speed in m/s, f is the 5.9GHz IEEE 802.11p control channel frequency and $c = 3 \times 10^8$m/s. There are L multipath components of unit value fading amplitude A_n, with varying phase ϕ_n and arrival azimuth α_n that is uniformly distributed over $(\pi, -\pi)$. This Rayleigh channel is multiplied with an 8-tap exponentially decaying power delay profile (PDP) from the ETSI Channel B model [10] with 100ns mean rms delay spread. This delay spread is in agreement with highway measurements as reported in [11]. With plenty of space availability on vehicles, the diversity benefit of STBC (space-time block codes) multiple antenna schemes can also be exploited because antennas that can be placed sufficiently apart are spatially decorrelated.

In previous research work, typically a short safety message of around 500 bytes is used for safety broadcasts [12]. In our analysis, we assume a 512 bytes post-crash message block sent by the tagged vehicle at the application layer, that is partitioned into $K = 8$ source symbols (SSs) of 64 bytes each. This data is then encoded using the systematic Raptor code and transmitted as encoded symbols (ESs). Each of the generated ESs are independent from one another with a limitless number of possible ESs. The decoder need only to receive slightly more than K ESs in whichever order to successfully decode the post-crash message. On the other hand, for post-crash message using repetition codes, the K source symbols are no longer independent and need to be correctly received to be able to decode the message. Unless each of the K source symbols are received correctly at least once, the K source symbols are repeatedly resend. This is similar to a coupon collector problem to ensure a fair comparison between the two coding schemes. We assume that packet transmission at the application layer behaves similar to a binary erasure channel. The transport protocol for both Raptor codes and repetition codes simulation is the UDP (user datagram protocol).

IV. Safety Broadcast MAC Modeling

With multiple number of interfering vehicles, there is a possibility of MAC collisions thus a simplistic average random backoff model can no longer be made. A number of analytical studies using Markov Chains and stochastic processes have been developed to analyze the performance of the IEEE 802.11 DCF MAC.Bianchi [13] utilized a bi-dimensional Markov chain as a function of backoff stage and backoff counter to define the saturation throughput of a finite number of stations n, with always non-empty transmission queue. It is assumed that the probability of collision seen by a packet being transmitted on the channel p, is constant and independent for each transmitted packet and is given by eq. (5), where τ is the probability that a station transmits a packet in a generic slot time. With safety broadcast where the backoff stage in always zero i.e. backoff counter within range [0,CW_{min}], τ will be independent of p as shown in eq. (6).

$$p = 1-(1-\tau)^{n-1} \tag{5}$$

$$\tau = \frac{2}{CW_{min}+1} \tag{6}$$

The average end-to-end delay of a source symbol can be determined using eq. (7), where $E[N_{slot}]$ is the average number of slot times required for successfully transmitting a packet and $E[L_{vs}]$ is the average length of the virtual slot time considering idle, collision and successful packet transmission periods[14].

$$E[D] = E[N_{slot}]\cdot E[L_{vs}] \tag{7}$$

$$E[N_{slot}] = \frac{1}{\tau\cdot(1-p)} \tag{8}$$

$$\begin{aligned} E[L_{vs}] \quad = \quad & (1-P_{tx})\cdot T_{slot}+P_{tx}\cdot P_s\cdot T_{success} \\ & +P_{tx}\cdot(1-P_s)\cdot T_{collision} \end{aligned} \tag{9}$$

The delay calculation is also dependent on finding out the probability that at least one vehicle transmits in the slot time P_{tx}, the probability of transmission success P_s and average times that the medium is sensed busy due a successful transmission $T_{success}$ or a collision $T_{collision}$ respectively.

$$P_{tx} = 1-(1-\tau)^n \tag{10}$$

$$P_s = \frac{n\cdot\tau\cdot(1-\tau)^n}{1-(1-\tau)^n} = \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{P_{tx}} \tag{11}$$

$$T_{success} = T_{collision} = DIFS + T_{data} \tag{12}$$

The transmitted packet T_{data} consists of the PLCP preamble and header, which are represented by 5 OFDM symbols; the upper layer headers sizes, $N_{layer\,headers}$ are 8 bytes for UDP, 20 bytes for IP, 34 bytes for MAC and 24 bytes for PHY; number of coded bits per OFDM symbol, N_{DBPS} for 6 Mbps QPSK 1/2 mode is 48 bits; and T_s is the OFDM symbol duration of $8\mu s$.

$$T_{data} = T_{PLCP\,preamble} + T_{PLCP\,header} + \lceil \frac{N_{layer\,headers} + N_{payload}}{N_{DBPS}} \rceil \cdot T_s \quad (13)$$

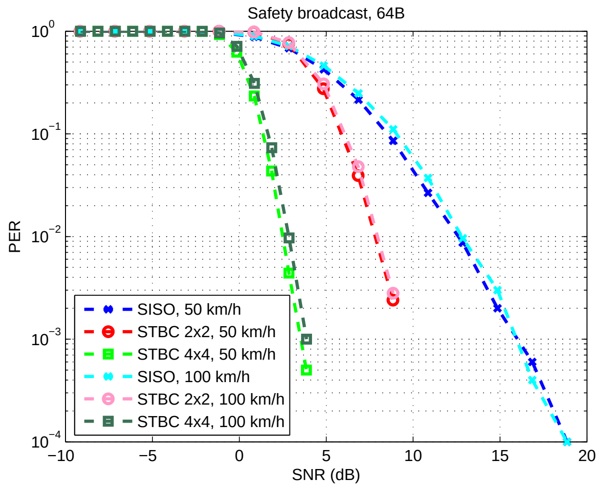

Fig. 3. Safety broadcast: packet error performance

V. Numerical Results

We adopted a numerical approach by means of a detailed physical layer model that among other takes into consideration an accurate packet error rate (PER) analysis based on the IEEE 802.11p OFDM (Orthogonal Frequency Division Multiplexing) scheme, a novel channel tracking mechanism using a midamble [15], for both single antenna and STBC (Space-Time Block Code) multiple antenna schemes. More details can be found in our previous work [6]. The packet error rate curves obtained from our detailed physical layer simulator for different antenna schemes and average speeds are shown in Figure 3. The PER curves are used as the packet erasure rates of the systematic Raptor codes at each specific SNR (signal to noise ratio) that is translated into distance of a receiving vehicle to the tagged vehicle using a free space propagation model. All simulation parameters are summarized in Table I.

We specify two discrete values of n interfering vehicles for the different highway traffic density. Because the Bianchi model assumed that nodes are under saturation condition, we specify that the interfering nodes for low density traffic is 10 and for high density traffic, n is defined as 20.

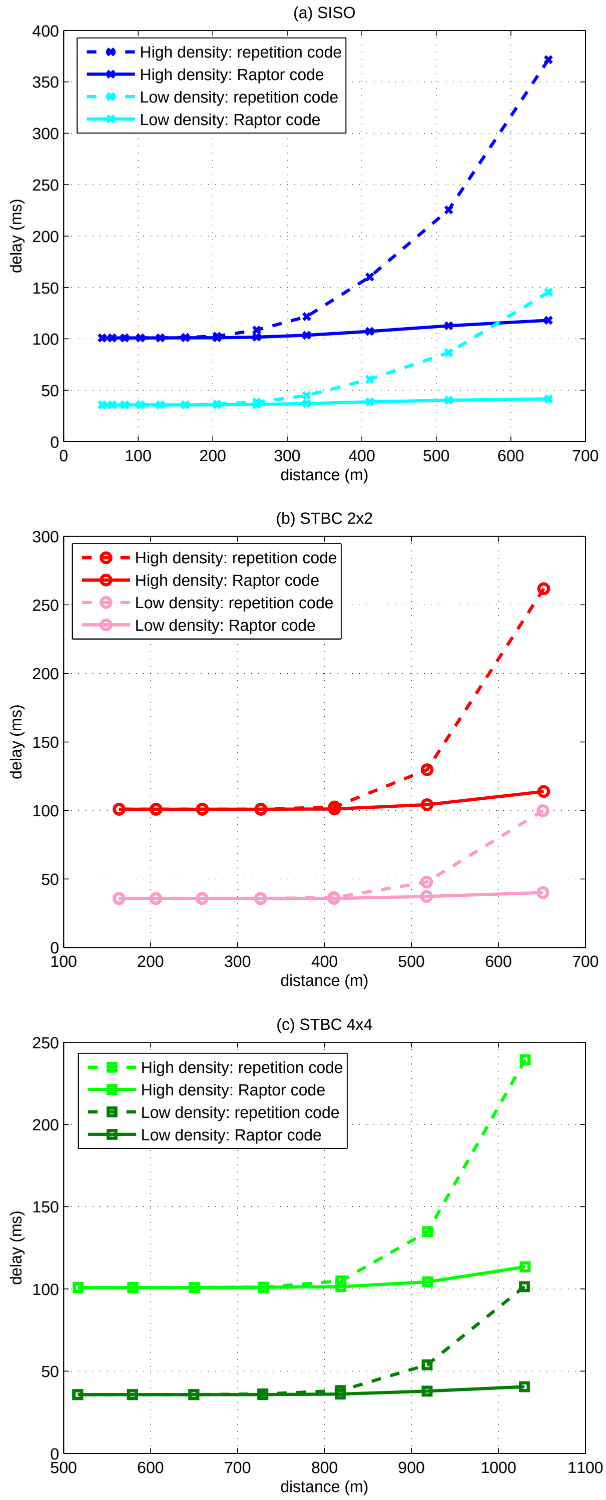

Fig. 4. Safety broadcast with interference: End-to-end delay performance

The end-to-end delay performance of Raptor codes against repetition code for different antenna schemes are as shown in Figure 4. It is shown that doubling the number of interfering nodes will result in more than double increment to the end-to-end delay. Raptor codes decreased the end-to-end delay by around 50% to 60% of for high density traffic and around 60% to 70% for low density traffic. Raptor codes are able to meet the ETSI specification of 100ms latency requirement for safety applications, such as post crash message [16]. With repetition codes, this requirement can only be met by vehicles located very near to the tagged vehicle. For example, in high traffic density, the requirement can only be met for vehicles less than 200m away for SISO scheme, and 300m away for STBC 2x2 scheme. Spatial diversity is worth exploring for VANETs as it does not only extends the communication distance of the safety broadcast, but at the same time reduce the end-to-end delay especially for high traffic condition. For example, STBC 4x4 scheme using Raptor codes extends the range to around 1000m i.e. the ideal communication distance required by the IEEE 802.11p draft standard.

TABLE I
SIMULATION PARAMETERS

Parameters	Value	Parameters	Value
Transmit power, P_T	15 dBm	Packet length (source block)	512 B
Receiver Sensitivity	-90 dBm	Source symbol, K	8 (64 B)
Communication range, R	0.7 km	CW_{min}	15
Bandwidth, B	10 MHz	SIFS	$32\mu s$
Data rate, R_d	6 Mbps	Slot time, T_{slot}	$13\mu s$
Antenna height, $h_t = h_r$	1.5 m	Propagation delay	$1\mu s$
control channel frequency, f	5.9 GHz	PHY preamble	$40\mu s$

VI. CONCLUSIONS

In this paper, the performance comparison for a WAVE post-crash safety broadcast in ad hoc car-to-car communication networks have been investigated using a combination of analytical model and numerical analysis. Taking into consideration the draft IEEE 802.11p parameters and the random backoff MAC DCF procedure, we investigated an enhancement at the application layer and compared the performance of the repetition codes proposed in the standard with a novel coding mechanism using a systematic Raptor code. At the physical layer, the packet error rate performance based on multiple antenna schemes and a time-correlated Rayleigh fading channel from a detailed physical layer simulator performance is used to give a more realistic and accurate representation to the analysis. To the best of our knowledge, our work is the first initiative to evaluate a rateless code in a VANET safety broadcast application.It is shown that the Raptor code improves between 50% to 70% of the end-to-end delay performance as compared to repetition codes. These early results are a clear indication and motivation towards the consideration of rateless code for safety broadcast applications. In reality, safety broadcast involves much less traffic (unsaturated condition) with higher number of interfering nodes. For example, analysis in [17] assumes unsaturated traffic with up to 100 interfering nodes. Future work will look into an analytical model based on unsaturated channel conditions.

ACKNOWLEDGMENT

Nor Fadzilah Abdullah would like to thank the Malaysian Ministry of Higher Education and Universiti Kebangsaan Malaysia for funding this work. Special appreciation is expressed to Dr. Dino Sejdinovic for his guidance on implementation of 3GPP systematic Raptor code.

REFERENCES

[1] European Road Safety Observatory, “Annual statistical report 2007.” [Online]. Available: http://euroris.swov.nl/safetynet/fixed/WP1/2007/SN-1-3-ASR-2007.pdf
[2] A. Shokrollahi, “Raptor Codes,” *IEEE Transactions on Information Theory*, vol. 52, no. 6, pp. 2551–2567, Jun. 2006.
[3] S. Yousefi, T. Chahed, M. Moosavi, and K. Zayer, “Comfort Applications in Vehicular Ad Hoc Networks Based on Fountain Coding,” in *IEEE 71st Vehicular Technology Conference (VTC-Spring ’10)*, May 2010.
[4] M. Sardari, F. Hendessi, and F. Fekri, “DMRC: Dissemination of Multimedia in Vehicular Networks Using Rateless Codes,” in *IEEE INFOCOM Workshops 2009*, Jun. 2009, pp. 1–6.
[5] P. Cataldi, A. Tomatis, G. Grilli, and M. Gerla, “A Novel Data Dissemination Method for Vehicular Networks with Rateless Codes,” in *IEEE Wireless Communications and Networking Conference (WCNC ’09)*, Apr. 2009, pp. 1–6.
[6] N. F. Abdullah, A. Doufexi, and R. J. Piechocki, “Spatial Diversity for IEEE 802.11p Post-Crash Message Dissemination in a Highway Environment,” in *IEEE 71st Vehicular Technology Conference (VTC-Spring ’10)*, May 2010, pp. 1–5.
[7] N. F. Abdullah, R. J. Piechocki, and A. Doufexi, “Raptor code for wireless ad hoc vehicular safety broadcast,” in *IEEE Globecom 2010 Workshop on Mobile Computing and Emerging Communication Networks (MCECN, GLOBECOM’10)*, Miami, Florida, USA, Dec. 2010.
[8] 3GPP TS 26.346, *Multimedia Broadcast/Multicast Service (MBMS); Protocols and codecs*, Std., Rev. 9.3.0, Jun 2010. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/26346.htm
[9] ETSI TS 102 472, *Digital Video Broadcasting (DVB); IP Datacast over DVB-H: Content Delivery Protocols*, Std., Rev. 1.2.1, Dec 2006. [Online]. Available: http://pda.etsi.org/exchangefolder/ts_102472v010301p.pdf
[10] J. Medbo and P. Schramm, “Channel Models for HIPERLAN/2 for Different Indoor Scenarios,” *ETSI EP BRAN/3ERI085B*, Mar. 1998.
[11] D. Matolak, I. Sen, W. Xiong, and N. Yaskoff, “5 GHz wireless channel characterization for vehicle to vehicle communications,” in *Proceedings of IEEE Military Communications Conference (MILCOM ’05)*, vol. 5, Oct. 2005, pp. 3016–3022.
[12] M. Torrent-Moreno, S. Corroy, F. Schmidt-Eisenlohr, and H. Hartenstein, “IEEE 802.11-based one-hop broadcast communications: understanding transmission success and failure under different radio propagation environments,” in *9th ACM International Symposium on Modeling Analysis and Simulation of Wireless and Mobile Systems (MSWiM ’06)*, New York, USA, 2006, pp. 68–77.
[13] G. Bianchi, “Performance analysis of the IEEE 802.11 distributed coordination function,” *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, Mar. 2000.
[14] P. Chatzimisios, V. Vitsas, and A. Boucouvalas, “Throughput and delay analysis of IEEE 802.11 protocol,” in *Networked Appliances, 2002. Liverpool. Proceedings. 2002 IEEE 5th International Workshop on*, 2002, pp. 168–174.
[15] S. I. Kim, H. S. Oh, and H. K. Choi, “Mid-amble aided OFDM performance analysis in high mobility vehicular channel,” in *IEEE Intelligent Vehicles Symposium (IVS ’08)*, Jun. 2008, pp. 751–754.
[16] ETSI TR 102 638, *Intelligent Transport Systems (ITS), Vehicular Communications (VC), Basic Set of Applications, Definitions*, Std., Rev. 1.1, Jun 2009. [Online]. Available: http://www.etsi.org/deliver/etsi_tr/102600_102699/102638/01.01.01_60/tr_102638v010101p.pdf
[17] X. Ma, X. Chen, and H. Refai, “Unsaturated Performance of IEEE 802.11 Broadcast Service in Vehicle-to-Vehicle Networks,” Sep. 2007, pp. 1957–1961.